New Insights into Car-following Behavior on Freeways Based on High Resolution Vehicle Data

Thesis

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Abstract

This research seeks to find a better understanding of how a given driver in congestion responds to the speed change of the vehicle ahead of them. This car-following behavior was studied based on a high-resolution data set collected by a probe vehicle on I-71 in Columbus, OH. This work used Matlab to analyze the speed-spacing relationship in the car-following regime and identify factors that may have impact on such relationship. Several factors were identified that appear to impact the speed-spacing relationship: time offset between the leader and follower, relative speed from adjacent lanes, and the rate of lane change maneuvers.

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Gao, H., Kong, S., Zhou, S., Lv, F., Chen, Q. "Automatic Extraction of Multi-Vehicle Trajectory Based on Traffic Videotaping from Quadcopter Model", *Applied Mechanics and Materials*, Vol. 552, pp. 232-239, 2014

Field of Study

Major Field: Civil Engineering

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Car-following theory seeks to describe the way that drivers respond to a change in the motion of a leading vehicle while traveling in the single lane on the road (Wang & Jin, 2012). Typically, these studies seek to model the relationship of how a driver chooses acceleration in response to the speed and acceleration of its leading vehicle, and the gap (or spacing) between the two vehicles.

Although this area has been an active field of study for 80 years, much is still unknown about the fine details. According to Bevrani et al. (2012), the Gazis–Herman–Rothery (GHR) model (Gazis et al., 1959; Herman et al., 1959; Rothery, 1997) is among the most commonly used car following models and the GHR model describes the response of a following driver as, “sensitivity times stimulus” to establish the gap and acceleration of the following vehicle. However, the GHR model is far from perfect. The original models were developed purely based on mathematical deduction rather than empirical study. Experimental data was only used to demonstrate the model after it was developed.

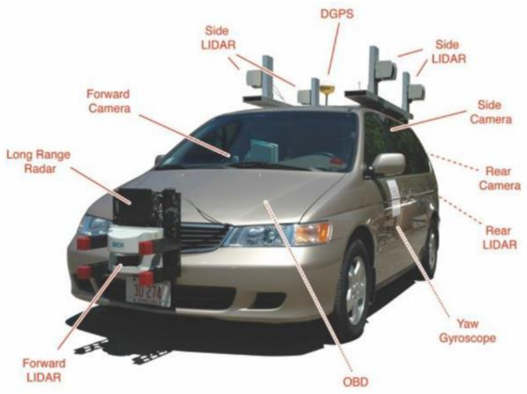

Figure 1: The instrumented probe vehicle

The details of car-following behavior is rarely empirically studied because of the difficulty of collecting sufficiently accurate data given the high speeds and large number of vehicles involved. As noted by Haight (1963), “There is a need for models which take into consideration the sampling of traffic and subsequent statistical analysis”. This research uses data collected by an instrumented prove vehicle equipped with localization sensors (DGPS and inertial navigation) for positioning and perception sensors (LIDAR and radar) to measure the gap to the leading and following vehicles in the same lane, as shown in Fig. 1 (Coifman et al., 2016). Coifman et al. cleaned the position data for the probe vehicle and ambient vehicles, and then measured other factors, e.g., speed and acceleration; thus, providing a cutting-edge data set for this research to construct empirically based car following models.

My research is primarily focused on is the speed-gap relationship (or after removing the constant vehicle length, the speed-spacing relationship becomes the speed-gap relationship). This relationship was examined by plotting and manipulating the empirical data collected from the probe vehicle, starting with the speed of the vehicle versus the gap to the leading vehicle. This research seeks further understanding of the factors that impact the traffic state equilibrium— in particular, how acceleration/deceleration, lane change maneuvers, and other factors may perturb the fundamental relationship.

By examining the speed-gap relationship, this research found that in the car-following regime, the speed-spacing relationship for a given driver is not a well-defined curve (as is typically employed by conventional models), instead, it is a scattered progression that often exhibits a counter-clockwise cycle in the speed-spacing plane. As shown herein, the nature of the looping changes with the addition of time offset. This work also investigated the impact of the relative speed from adjacent lane and the frequency of lane change maneuvers on the behavior of a driver in the car following regime, as reflected in the speed-spacing plane.

Overview

In most car following models, the speed-spacing relationship (where again, spacing = gap + vehicle length) is either explicitly or implicitly embedded in the model. Usually these models are based on an idealized assumption of either a single functional form of a static curve in the speed-spacing plane for all drivers or a small family of curves that are typically static for a given driver. It is generally accepted that within the car-following domain that speed is below free speed, i.e., a given driver is traveling slower than they would choose for the given roadway if they were not constrained by their leader. Furthermore, that spacing increases with speed (and vice versa, as the causality likely follows in both direction). These relationships are represented with a functional form that has a single speed for a given spacing, e.g., the linear curve Figure 2, though the relationship does not have to be linear. Note that term gap is different from spacing, where spacing is the distance from the rear bumper of the lead vehicle to the rear bumper of the following vehicle while the gap excludes the physical length of the following vehicle (a constant value) and is only rear bumper of lead to front bumper of follower. Empirically though, the speed verses gap relationship exhibits considerable scatter, e.g., the scattered point cloud in Figure 3, and at best, only the central tendency follows a static functional form.

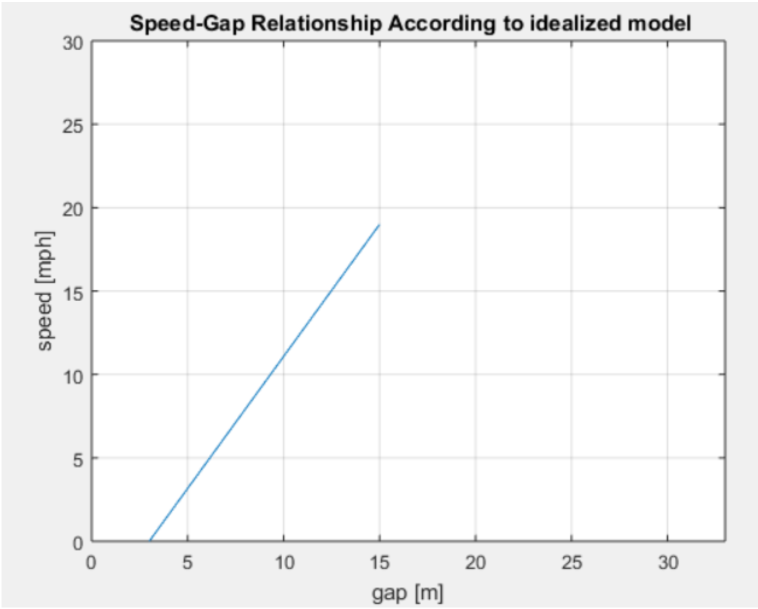

Figure 2: Idealized speed-gap relationship for car-following

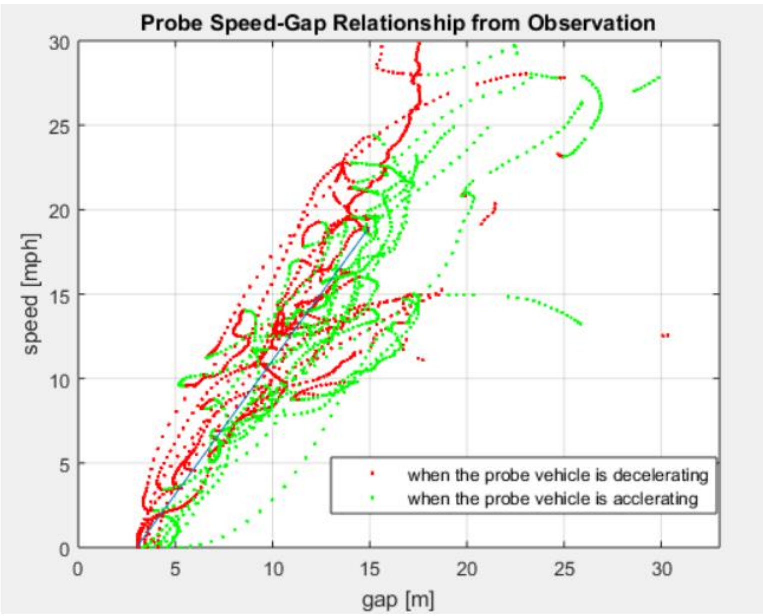

Figure 3: An example of the empirically observed speed-gap relationship over 15 miles

The green points in Figure 3 come from periods when the probe vehicle is accelerating, and the red points from when the probe vehicle is decelerating. Close inspection of the progression reveals that it is very rare that a driver goes a constant speed when car following at a certain gap. Instead of staying on the ideal curve, generally the driver is exhibiting counter-clockwise loops about some unobserved central curve. This cycle arises from changes in the lead vehicle speed and a lag in response from the follower (see, e.g., Newell, 1962). By definition the cycle is continuous, but the following explanation will arbitrarily start with the deceleration arc from the top right corner of Figure 4 and progressing counter clockwise. The lead vehicle starts to decelerate but initially the follower maintains their current speed, so the gap shrinks. At some point the follower responds to the shrinking gap by decelerating, and so the speed drops. Usually (but not always) the gap continues to drop throughout the deceleration arc. Regardless, the follower is closer than average to the leader during this downward progression, hence the desire to continue decelerating. The process is flipped for the acceleration arc from the bottom left corner. First the leader accelerates while the follower maintains their speed, creating a large gap, the follower responds a short time later by accelerating, usually the gap continues to grow throughout the acceleration arc, and the follower is further than average from the leader during this upward progression, hence the desire to continue accelerating.

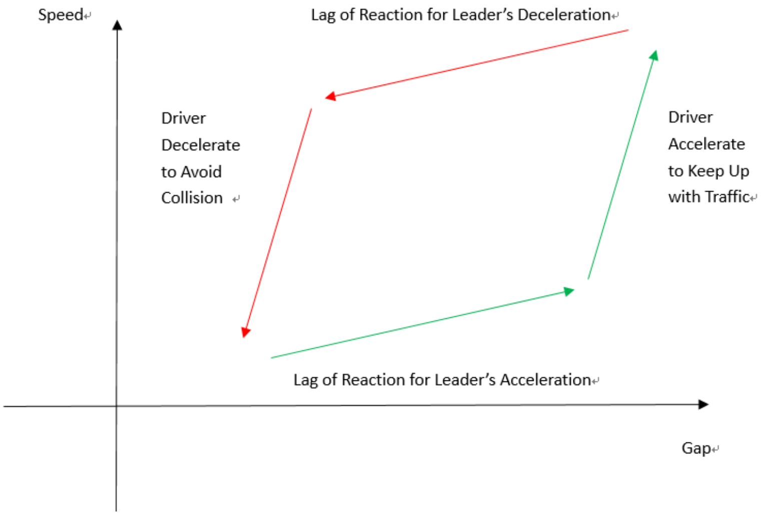

Figure 4: Emergent looping progression in the speed-gap plane

Empirical study

This section explores various factors that are embodied in the speed-gap relationship or that may affect that relationship. The factors that have been studied in the scope of the research includes the impact of time offset on the speed-gap relationship,

Experiments in time offsets

In the research the impact of time offset was studied by shift the speed by a small time-step, τ. The speed-gap relationship was then regenerated as speed at time t+τ vs. gap at time t. The process was repeated for a certain range of τ, result was found that adding time offset makes the acceleration and the deceleration legs of the cycle coverage to the mid-point and thus flatten the loop. As shown in figure 5a and 5b, while figure 5a shows the original speed-gap relationship as loop similar to the plots mentioned above, then figure 5b shows the result of adding time offset of $\tau^* = 1$s as it flattens the loop. For the time offset that has been studied I found that a shift of $\tau^* = 1$ sec does the best job to flatten the loops.

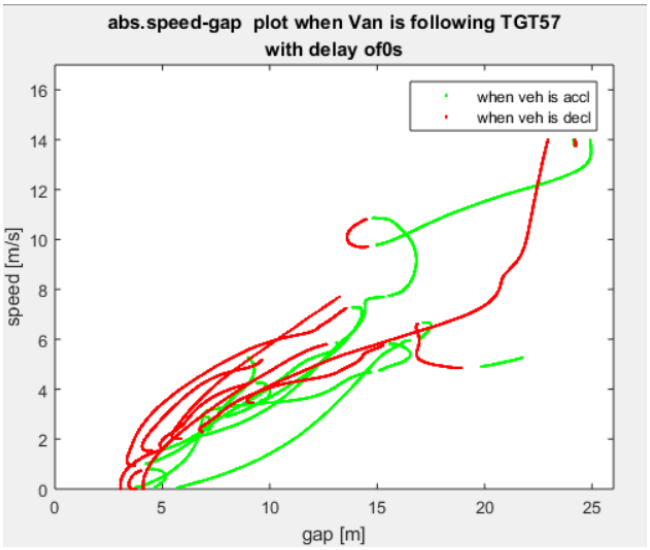

Figure 5a: Original Speed-Gap Plot of Car-following

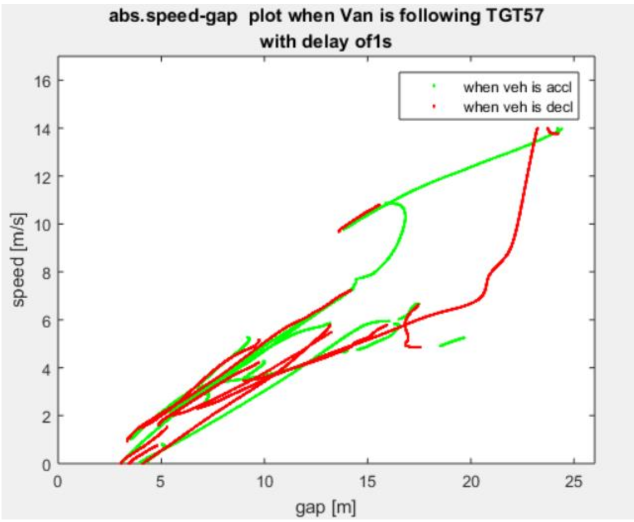

Figure 5b: Speed-Gap Plot with time offset of 1s

The meaning of the “optimal” time offset as well as the curve result from flatten loop has yet to be found. At this point it is hypothesized that the slopes of the flattened loops are related to the acceleration during the given disturbance, while the optimal time offset is related to the response time for the follower driver. There is certainly more research needed to be done to understand the physical source of this behavior.

Other factors that may impact the driving behavior

The discussion of Figure 4 has already explained how changes in the lead vehicle speed and the follower's lag in response can give rise to a counter clockwise cycle in the speed-gap plane. There is recent evidence to suggest that external factors can also impact the speed-spacing relationship exhibited by drivers. Ponnu and Coifman (2015) used loop detector data to show that in aggregate, as the adjacent lane speed drops drivers in the subject lane become more conservative by adopting a larger spacing at a given speed. While Daganzo (2002) speculates that in merging sections drivers become more aggressive and take tighter spacing to prevent other drivers from entering their lane in front of them. This section looks for evidence in the probe vehicle data to support the influence of the adjacent lane speed (following Ponnu and Coifman) and then attempts to quantify the rate of lane change maneuvers on different segments to see if different rates of lane change maneuvers impact how closely drivers are willing to follow their leaders (following Daganzo).

Relative speed from adjacent lane

This section first considers situations in which there is a high relative speed between the probe vehicle and the adjacent lane. In making the comparison, this research filtered the data according to its relative speed to an adjacent lane (left or right lane). The methodology computes the ratio between the speed of the probe vehicle relative to the speed in the given adjacent lane. Following that, the ratio is compared with a threshold (currently set to: 1.14x the adjacent lane speed), the data points that have the ratio more than the threshold means it is at least 14% faster than the given adjacent lane, which suggest that it have a high relative speed compared to one of adjacent lane. After the data were filtered and re-plotted with the original ones, a comparison can be made on the data that pass the filter and the data related to conservative driving behavior.

Figure 6 shows the result of the comparison, where the cyan curve shows all of the decelerations in the day, the red points show the measurements that pass the relative speed filter from the right (i.e., the probe vehicle is moving at 114% the speed of the vehicles in the lane to the right), blue circles show the measurements that pass the relative speed filter to the left, (i.e., the probe vehicle is moving at 114% the speed of the vehicles in the lane to the left). As shown in the figure, the blue circles tend to fall to the right of the point cloud, suggesting that in deed, when the left lane is moving slower that the subject lane adopts larger gap. Although this comparison is far from conclusive, it is consistent with what one would expect if Ponnu and Coifman (2015) is correct. On the other hand, the red points tend to fall left of center in the cloud, which is seemingly counter to the argument since the probe vehicle is moving faster than the right lane but the driver is often less conservative than average. However, in normal traffic the fastest vehicles should be traveling on the left, and drivers should normally expect the lane to the right to move a little slower than a subject lane. So it is also possible that the lane to the right is not slow enough to elicit a response from the probe vehicle.

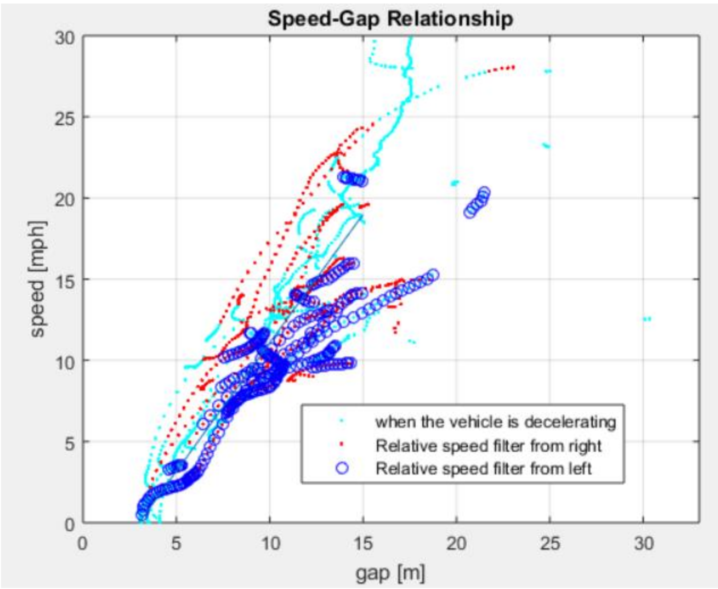

Figure 6: Speed-gap relationship during decelerations, the red dots show the data points that exceed the 14% threshold above the lane to the right while the blue circles show the data points that do so from the lane to the left.

Drilling deeper in to the deceleration arc, consider Figure 7. The highlighted points show two successive counter clockwise loops in the speed-gap plane by the probe vehicle. Of note in this case is the fact that the deceleration arc on the second loop is almost 10 ft to the right of that from the first loop, indicating that the driver is more conservative on the second loop at the given range of speeds. To check whether the larger gap correspond to lower adjacent lane speed, the two plots on the bottom of figure 7 show that the second loop corresponds to a period of high relative speed to both adjacent lanes. Each data point marked with a given colored arrow corresponds to the exact same point throughout the four subplots. In fact during this second loop (the one to the right in Figure 7A) there is in fact a brief period where the probe vehicle exhibited a clockwise progression in the speed-gap plane (bounded by the red and blue arrows). Looking at Figure 7B-D, it should be clear that during this period the lane to the left was completely stopped and the lane to the right was mostly stopped, hence, the larger gap of this second loop is consistent with the expectation of more conservative gap at higher relative speed to the adjacent lane(s).

In reality, the clockwise progression (convex along the curve) may not only mark the points where the driver takes a larger gap in preparation of potential speed drop (or another complex situation), it may also mark emergency braking. So, more work is necessary to find a conclusive and complete explanation for the more conservative gap.

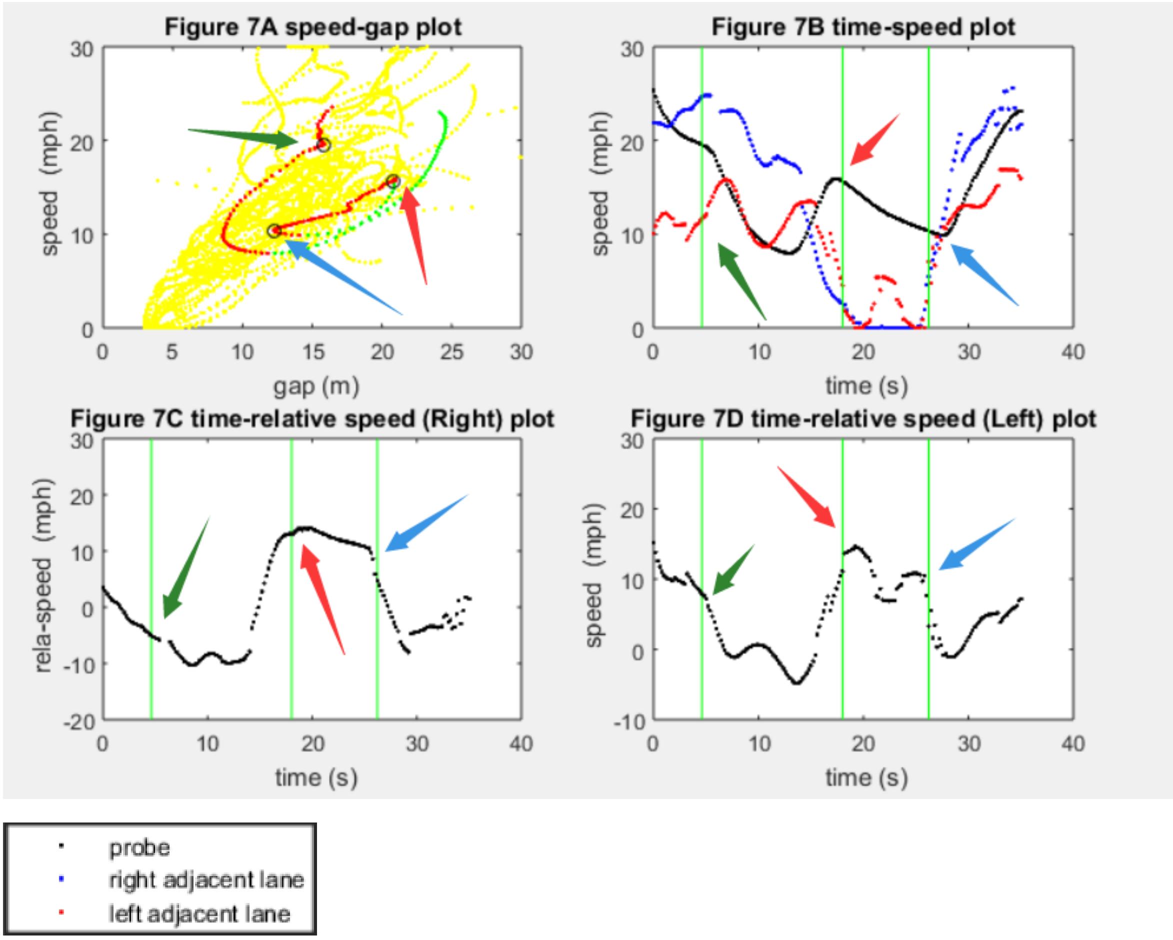

Figure 7: Plot for speed-gap and time-speed for same time period (time is in seconds after 17:12:15).

Rate of lane change maneuvers

There are many papers that suggest that drivers can aggressively protect their gap in an effort to try to keep other drivers from entering in front of them. On the other hand, within a weaving section it is also conceivable that a driver may instinctively become more conservative, taking longer gap which in turn actually creates more gaps for vehicles to enter the target lane. So this section looks for evidence that the rate of lane change maneuvers may somehow systematically impact the probe vehicle behavior.

When researching the impact of lane change maneuvers on the driver's behavior, this research identified three different segments on northbound I-71 to see if the rate of lane change maneuvers impacts driver spacing/gap. Research of this point mainly focuses on comparing the probe vehicle's speed-gap relationship across the three segments.

Figure 8: Division of the Segments

In this part, three sectors were selected and the work tallied the number of times the probe's leader changed lanes (expressed as a rate in number per km). Whenever the probe or the leading vehicle changed lanes a total of 20 sec bounding the maneuver is excluded to reduce the impact of the probe or the leading vehicle's change of lanes. After that is to regroup the data within each sector in speed bins whose width is 5 mph, in each speed bins, average gap was calculated. Following that a comparison was made on gap at given speed for road segment with different lane changing rate.

In the research, the three sector are divided as shown in the figure 8, and the rate of lane change maneuver (in # per km) was calculated as shown in Table 1, and Figure 9 shows the median gap for speed bin in the three sectors. As shown in the figure, for the three sectors studied, sector 2 had the highest lane change maneuver rate and it turns out to have the largest gap at most speeds, while sector 1 had the lowest lane change rate and it turns out to be the left-most curve. The results suggest that when the lane change maneuver rate is high, the driver tends to keep a larger gap compared to situation with small lane change maneuver rate, which means they are more conservative while driving.

Table 1: Lane Change Maneuver Rate for Each Road Segment

Segment	1	2	3
Leader Leaves Probe Lane	0.41	3.95	1.13
Leader Enters Probe Lane	0.4	1.31	0.45
Total leader Lane Change Maneuver	0.81	5.26	1.58

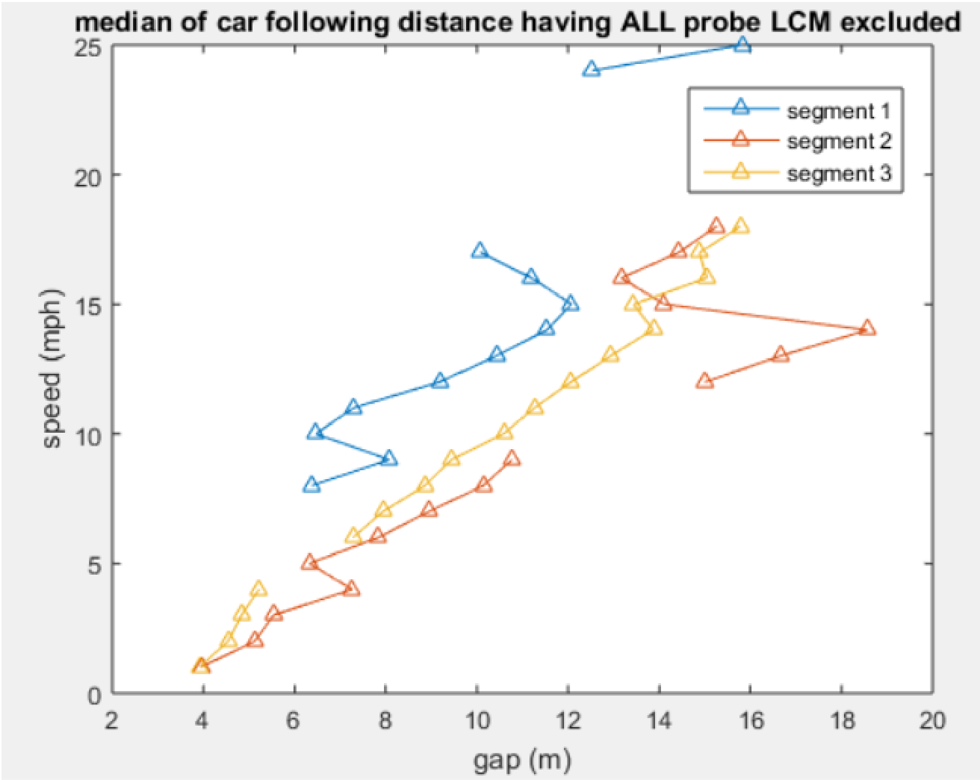

Figure 9: Median Gap for Each Speed Bin at the Three Segments

Lane change maneuvers in a weaving section

This research also looked for locations that have a large number of lane change maneuvers. The major weave, in Figure 11 was selcted with I-71 northbound entering on the top left, I-71 northbound exiting on the bottom right a few 100 ft past the location shown in the figure, and a connector ramp from I-70 westbound entering on the bottom left with much of the traffic destined for connector ramp to I-670 westbound exiting on the top right.

In order to get enough data for each location, this research uses data from multiple days to search for such a location. The data has been divided into speed bins with width of 5 mph, calculate average and median of gap for each speed bin. For the average gap and median gap get from the study location is compared with the average gap and median that gained from combining data from 9 locations that is selected equally spaced from the road segments. By comparing the gap data from the study location that lane change take place and average gap and median of other locations, the impact of lane change maneuver on driver's behavior can be observed. Figure 10 shows the comparison between the study location and all of the other locations. The data from all other location are plotted in yellow, and their average/median are shown in black with circle mark. The data from the study location are shown in blue with triangle marks.

The compares the results from the weaving section against the probe vehicle's performance over the entire tour. The study segment has a slightly larger than usual average and median gap at the given speed compared to other locations. Such result suggests that the driver tends to keep a larger spacing/gap when large number of lane change maneuver take place, which means the driver tend to be more conservative at this location.

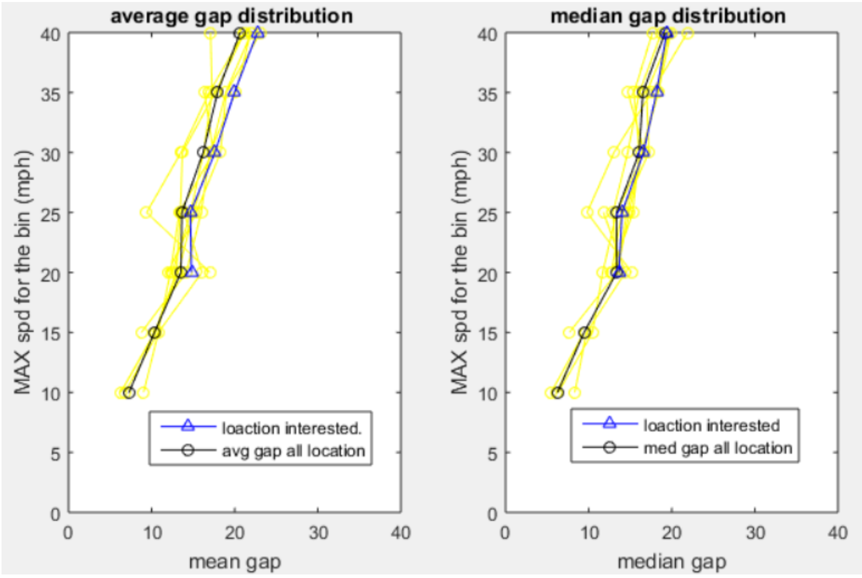

Figure 10: Comparison between Study Location and All Other Locations

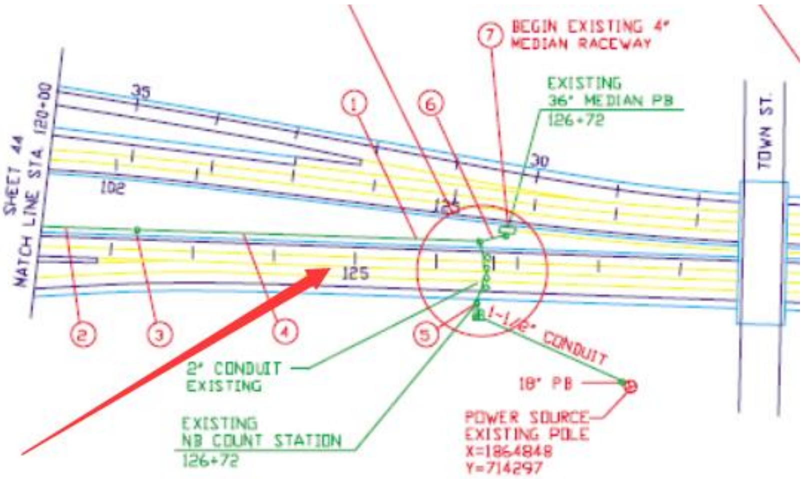

Figure 11 Geometry of the Study Location

Conclusions

This research found that the car-following process does not follow a well-defined curve that is commonly assumed by model. Because there is a certain time lag for the follower driver to react to the speed change of its leader, the change in gap (gap is just the spacing minus the vehicle length) between the two vehicles usually take place before the change in speed, which shows in the speed- gap plot as the acceleration pull the speed- gap curve to the right, while the deceleration pull the speed- gap curve to the left. Because of the difference between the process of acceleration and deceleration, rather than becoming a single well-defined curve, the relationship between the speed-gap typically exhibits a counter clockwise looping process. While the counter clockwise loop is under appreciated, it is not a new discovery. This work sought out many factors that could serve to systematically distort the speed-gap relationship and cause a driver to move with a larger or smaller gap than they would have otherwise done.

The first aspect presented was the fact that the speed- gap relationship changes form with the addition of time offset to the speed data. With a small time offset the counter clockwise the loops flatten. When an optimal time offset is added, the loop would converge to a well-defined curve. However, the meaning of the curve and time offset are not yet fully understood.

When car-following, there are certain cases when the follower driver tends to decelerate before the gap decrease, or tend to stay at a larger than usual gap. Certain case indicate that the driver is trying harder to avoid collision, meaning the driver is more conservative while driving. This research found evidence to suggest that both relative speed from the adjacent lane and that lane change maneuvers may cause a driver to take more conservative gap. However, these findings are only motivational, more extensive work is necessary to establish solid conclusive proof that the two factors are systematic triggers to elicit conservative driving (i.e., drivers taking larger gap).

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